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EXPERIMENTAL STUDY OF BLADE-TYPE HELICAL FLOW INDUCERS IN A 5/8-INCH ELECTRICALLY HEATED BOILER TUBE

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16. Abstract

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SUMMARY

The effects of blade-type flow swirlers on maximum exit quality of a 5/8-inch (1.59-cm) boiler tube were investigated. Data were obtained for various swirler spacings at a mass flow rate of 400 pounds per hour (5.0×10^{-2} kg/sec). Measurements of mass flow rate, heat flux, inlet water temperatures and pressures, outlet vapor temperatures and pressures, and axial wall temperature distribution for each run were made and are presented in tabular form. The quality, pressure drop, and critical heat flux for the plain tube are compared with values for tubes containing various numbers and spacings of flow swirlers. It was found that maximum exit quality increased from 0.30 to 0.60 by adding five swirlers. At a 0.3 exit quality, the pressure drop of the tube with five swirlers was 58 percent greater than for the plain tube.

INTRODUCTION

One of the problem areas of Rankine-cycle space power systems has been the design of high-performance, stable, compact boilers. The boilers must operate at a high heat flux with a minimum of entrained liquid in the outlet vapor stream. Boiling at high heat flux is also applicable to the design of cooling channels for solid-propellant rocket nozzles.

A common method used to reduce liquid entrainment has been to separate the liquid droplets from the vapor by swirling the two-phase mixture, thus centrifuging the liquid to the tube wall. This swirl has been obtained by inserting helical wires or twisted ribbons into the boiler tube, by coiling the tube, or by a combination of inserts and tube coiling. These approaches have resulted in varying degrees of improvement, as for example in the mercury boiler development program (refs. 1 to 4). Some other studies of the effect of swirling on boiler performance are described in references 5 to 7 for potassium boiling and references 8 to 12 for water boiling.

By centrifuging the liquid droplets to the tube wall, a quality higher than that obtained in a plain, straight tube is reached before film boiling occurs. Consequently, a higher heat flux is obtained before burnout occurs. These benefits are accompanied by a larger pressure drop across the boiler.

The object of this investigation was to determine the effects of blade-type helical flow swirlers at various axial spacings on the boiler exit quality, maximum heat flux, and overall pressure drop. The expected advantage of using blade-type swirlers over the types previously mentioned is higher exit qualities at much smaller pressure drops, resulting from the unobstructed flow passages between swirlers. The data from these tests are compared with those for a plain tube without swirlers.

The boiler tube used at this study was 0.625 inch (1.59 cm) in outside diameter, 0.031 inch (0.079 cm) in wall thickness, and 40.0 inches (101.6 cm) long. The swirlers were rotor elements obtained from turbine-type flowmeters, and were centrally installed in the test section without wall contact, and were nonrotating. Most of the data were obtained with boiling fluid flow rates of 400 pounds per hour (5.0×10^{-2} kg/sec). Limited data were obtained at other flow rates.

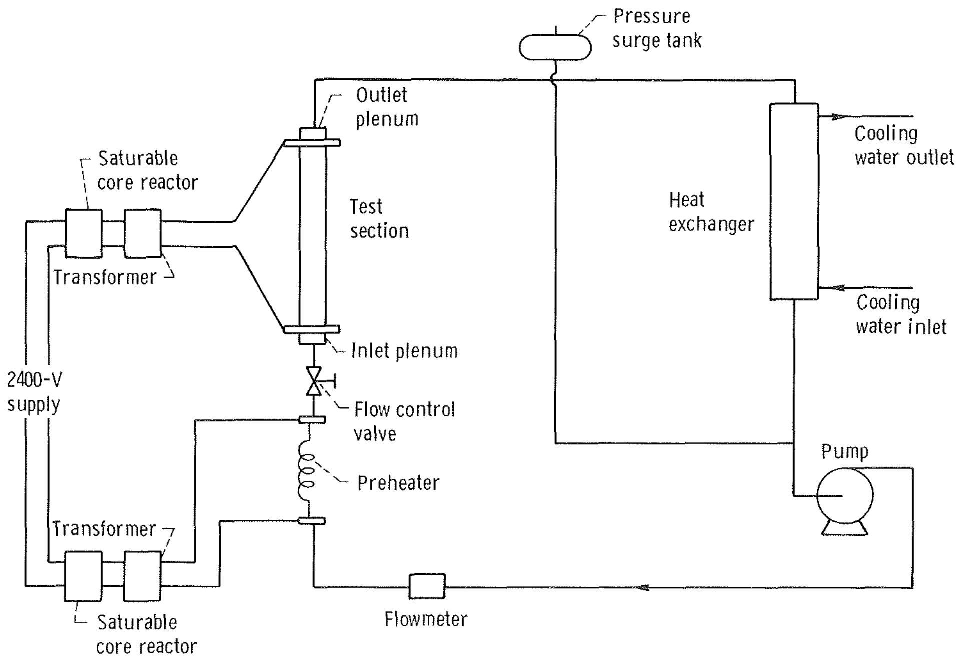

Figure 1. - System flow diagram.

APPARATUS

The experimental data were obtained with the test equipment described in detail in reference 13 and shown schematically in figure 1. The flow system is a closed loop in which water is recirculated by a gear pump. The major components of the loop consist of a resistance-heated stainless-steel preheater, a resistance-heated test section, and a water-cooled heat exchanger. The loop is pressurized at a surge tank which is connected to the loop at the pump inlet. The power for heating the test section is supplied by a saturable core reactor and a 270-kilovolt-ampere transformer.

The test sections used in this investigation were fabricated from 5/8-inch (1.59-cm) outside diameter, 0.031-inch (0.079-cm) wall thickness, type-304 stainless-steel tubing. Each test section was 40.0 inches (101.6 cm) long. Twelve-bladed rotor elements

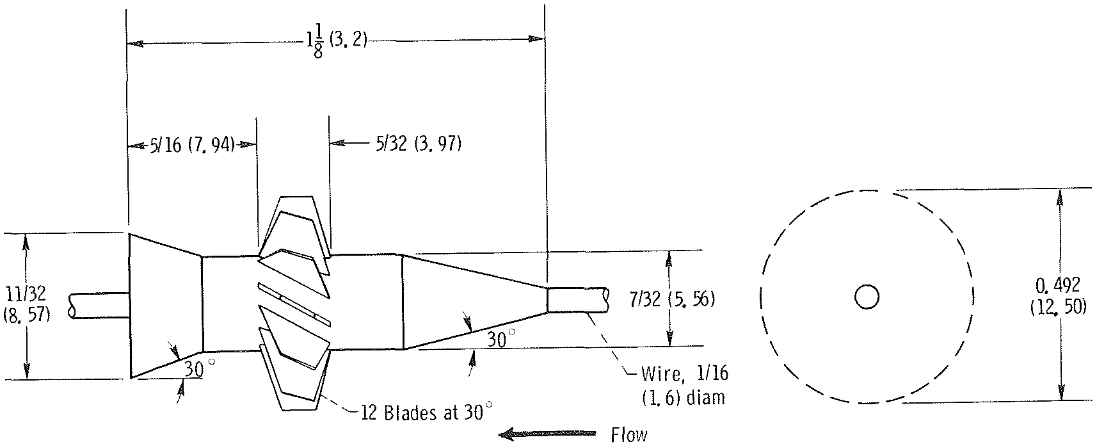

Figure 2. - Swirler diagram. (All dimensions are in inches (mm).)

(fig. 2) obtained from turbine-type flowmeters were used to swirl the flow and centrifuge the liquid droplets to the tube wall. The blades were located at a constant angle of 30° to the tube centerline. These nonrotating rotor elements were centrally installed within the test section by axially positioning them on a 1/16-inch (1.6-mm) diameter stainless-steel wire. This assembly was then centered within the test section tube. The wire and rotor elements were electrically insulated from the tube. The number of swirlers and their respective locations within the tubes are listed in the following table:

Test section	Number of swirlers	Locations of swirlers: distance from outlet, in. (cm)
A	0	--------
B	1	10 (25. 4)
C	1	5 (12. 7)
D	2	5 (12. 7) and 10 (25. 4)
E	2	4 (10. 2) and 8 (20. 3)
F	3	4 (10. 2), 8 (20. 3), and 12 (30. 5)
G	4	4 (10. 2), 8 (20. 3), 12 (30. 5), and 16 (40. 7)
H	5	4 (10. 2), 8 (20. 3), 12 (30. 5), 16 (40. 7), and 20 (50. 8)
I	6	4 (10. 2), 8 (20. 3), 12 (30. 5), 16 (40. 7), 19 (48. 2), and 22 (55. 9)
J	7	4 (10. 2), 8 (20. 3), 12 (30. 5), 16 (40. 7), 19 (48. 2), 22 (55. 9), and 25 (63. 5)

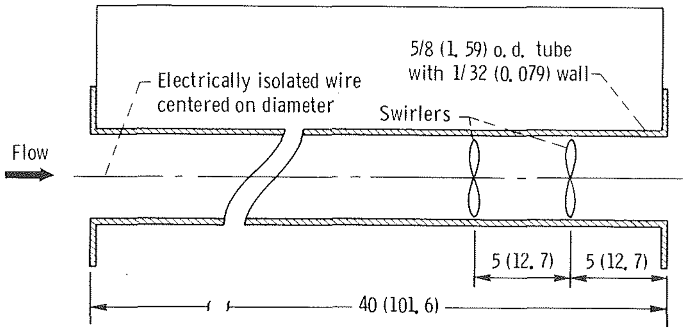

Figure 3. - Schematic diagram of test section D. (All dimensions are in inches (cm).)

The various configurations were tested in order of increasing number of swirlers, and labeled in alphabetical order. Figure 3 is a schematic diagram of a test section assembly. Copper bus bars were attached to both ends of the test section for applying electrical power. A disassembled test section is shown in figure 4.

The system flow rate was measured by a turbine-type flowmeter. The flowmeter output was read from a frequency converter and checked with a counter. The test section inlet and outlet pressures were measured by Bourdon-tube gages connected at the inlet and outlet plenums. Chromel-Alumel thermocouples were spotwelded to the outer wall of the test sections at the same circumferential position for all axial temperature measurements. Inlet and outlet bulk temperatures were measured by thermocouples in the liquid stream at the inlet and outlet plenums. All the temperatures were recorded on two single-pen self-balancing potentiometers. The alternating-current power to the test section was measured by a dynamometer-type wattmeter. The voltage drop across the test section was measured by a vacuum tube voltmeter.

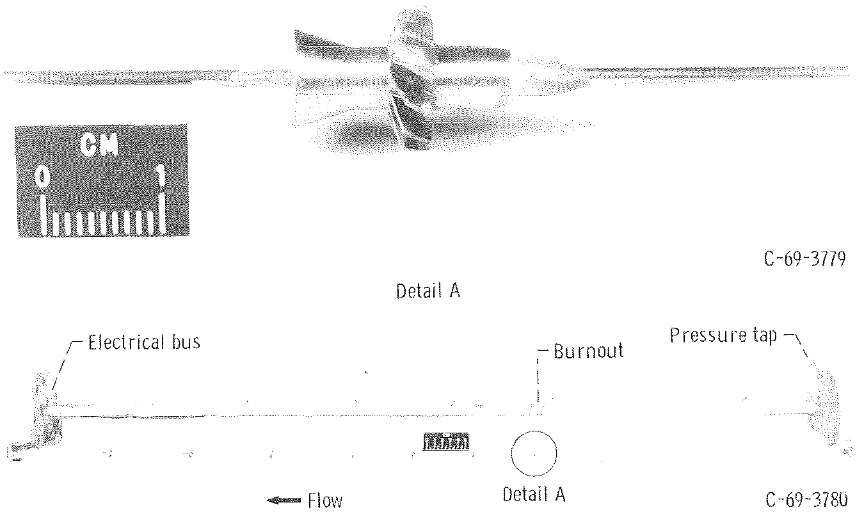

Figure 4. - Dissassembled test section (J).

PROCEDURE

Each day before data were taken, water was circulated and boiled in the test section. Noncondensable gases were vented from the system through a line connected to the high point of the loop. Dissolved gas content was maintained at less than 3 ppm by weight based on the average molecular weight of air.

In order to check the thermocouples, runs were made in which heat was applied to the preheater only. Since the heat losses from the test section to the surrounding environment were small, the tube outer-wall temperatures could be checked for consistency against the water bulk temperatures at the inlet and outlet plenums. This was done over the range of bulk temperatures encountered by adjusting the preheater power. The temperature recording instruments were calibrated before and after each series of runs.

The conditions for each run were established by setting the desired mass flow rate and increasing the power to the test section until physical burnout occurred. The inlet temperature was held constant at approximately 75° F (297 K). The burnout point was visually identified as the location at which a segment of the test section turned cherry red in color. Physical burnout and the cherry-red discoloration occurred almost simultaneously.

The criteria used for proceding from one configuration to the next (i. e., determining the number and spacing of the swirlers) was based on the results of the previous configuration tested. After each configuration was tested and the burnout location was determined, an additional swirler was added, or the previous ones were relocated. This

process was continued until no additional improvement in maximum exit quality occurred. Maximum exit quality was limited by system flow instabilities resulting from the interaction of the feed system and boiler because no boiler inlet stabilizing devices were used.

RESULTS AND DISCUSSION

The experimental data for all the configurations tested are tabluated in table I. Presented in this table are the mass flow rate, heat flux, inlet and outlet bulk temperature, and inlet and outlet pressures for each run. Exit quality was calculated from a heat balance and is presented in the same table. Also presented is an axial outer-tube-wall temperature profile for each run. A complete temperature profile was not always obtained for a burnout condition because of the need to shut down the test apparatus. A summary tabulation for the overall pressure drop across each test section configuration at the same heat flux and mass flow rate is presented in the following table:

[Heat flux, 350×10^3 Btu/(hr)(ft^2) (1.1×10^6 W/m^2); flow rate, 400 lbm/hr (5.0×10^{-2} kg/sec).]

Test section	Exit quality, percent	Pressure drop, ΔP	
		psi	kN/m^2
A	29.9	7.0	4.8
B	32.2	8.0	5.5
C	29.2	8.0	5.5
D	28.9	8.0	5.5
E	29.8	8.5	5.9
F	29.1	8.0	5.5
G	28.7	10.0	6.9
H	30.1	11.0	7.6
I	30.0	10.5	7.2
J	29.1	11.0	7.6

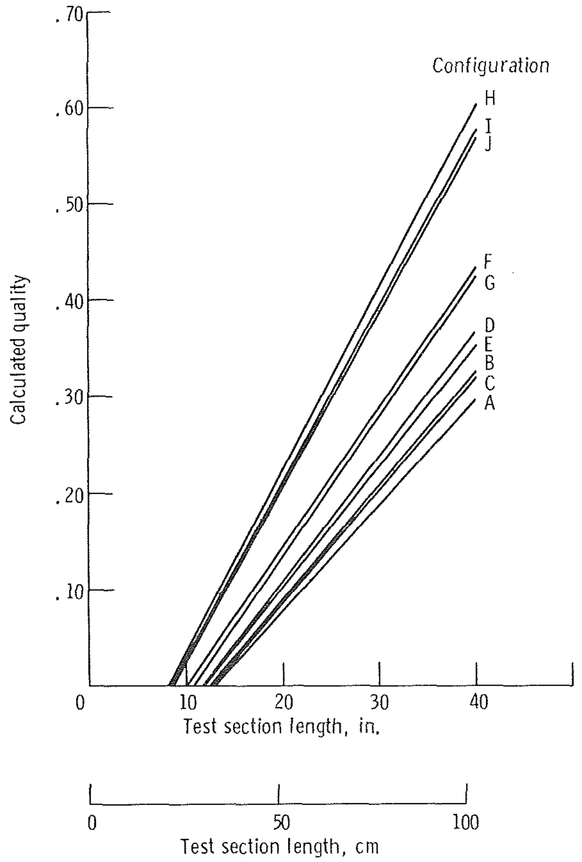

Figure 5. - Calculated thermodynamic quality as function of length, for maximum exit quality with each configuration tested. Flow rate, 400 pounds mass per hour (5.0×10^{-2} kg/sec).

Calculated thermodynamic quality as a function of length for tests in which maximum exit quality was achieved with each configuration at a flow rate of 400 pounds per hour (5.0×10^{-2} kg/sec) is presented in figure 5. The increase in quality at constant length with increasing number of swirlers is apparent. The maximum quality obtained was approximately 0.6 (configuration H with five swirlers). When configurations I and J, which contained six and seven swirlers, respectively, were tested, the exit quality did not improve. As shown in the preceding table, the increase in pressure drop at 0.3 exit qual- between configuration H and A (plain tube with no swirlers) was from 7 to 11 psi (4.8 to 7.6 kN/m^2). This was a 58-percent increase in pressure drop. The experiments in reference 11 showed a 400 percent increase in pressure drop for a helical wire insert at a pitch-to-diameter ratio of 1.9 over that for the plain tube at a quality of 0.30.

The maximum exit quality as a function of flow rate for configurations A, D, and H is shown in figure 6. As expected, an increase in quality was observed with decreasing

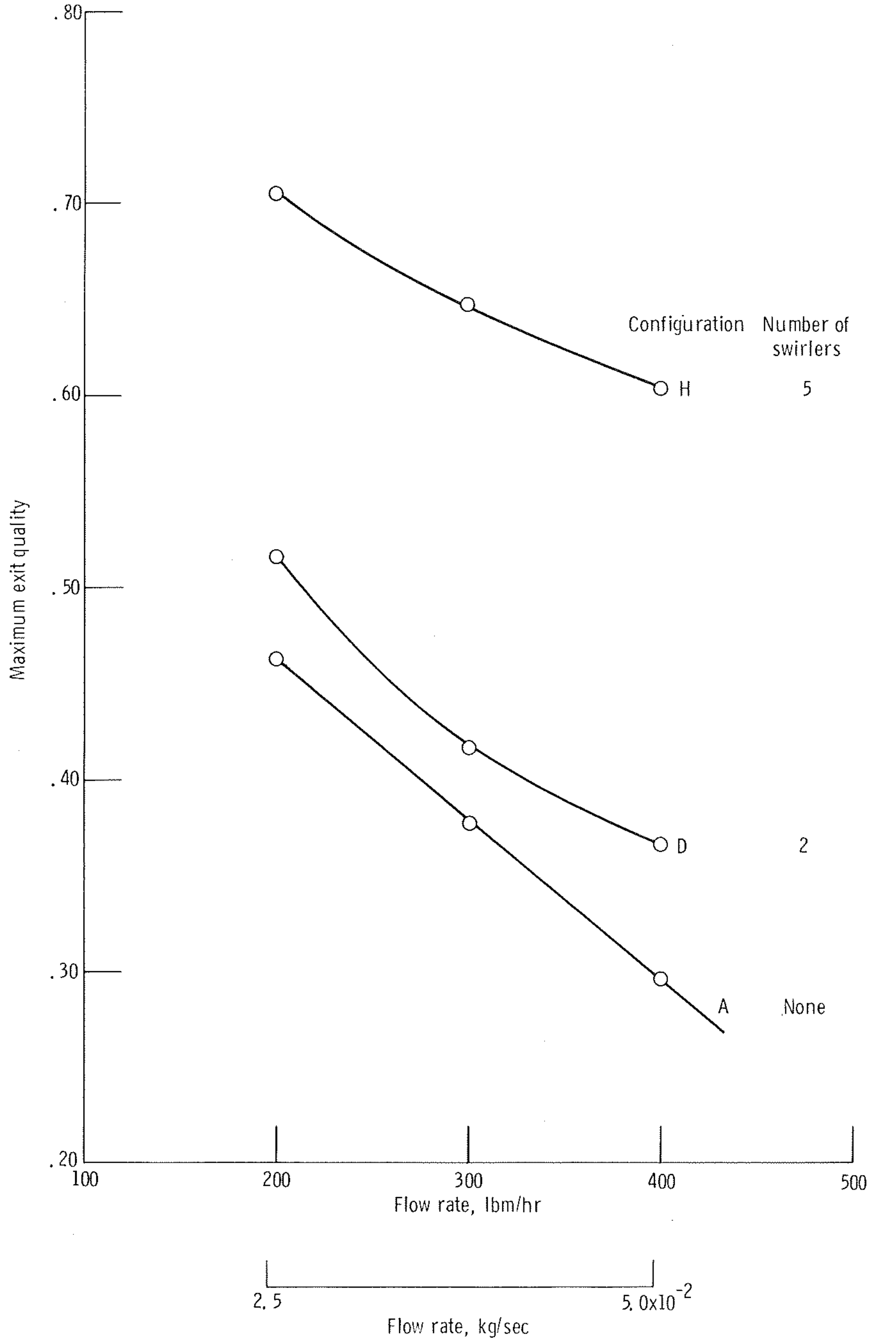

Figure 6. - Maximum exit quality as function of flow rate for configurations A, D, and H.

flow rate. However, the rate of increasing quality is somewhat greater for the plain tube (configuration A) than for configuration H.

A chart summarizing the results of all the configurations tested is presented in figure 7. Maximum quality and heat flux are charted for all configurations. The calculated start of the boiling region is indicated with respect to the test section length for all configurations tested. The calculated quality at the point of burnout is shown in parentheses under the point of burnout.

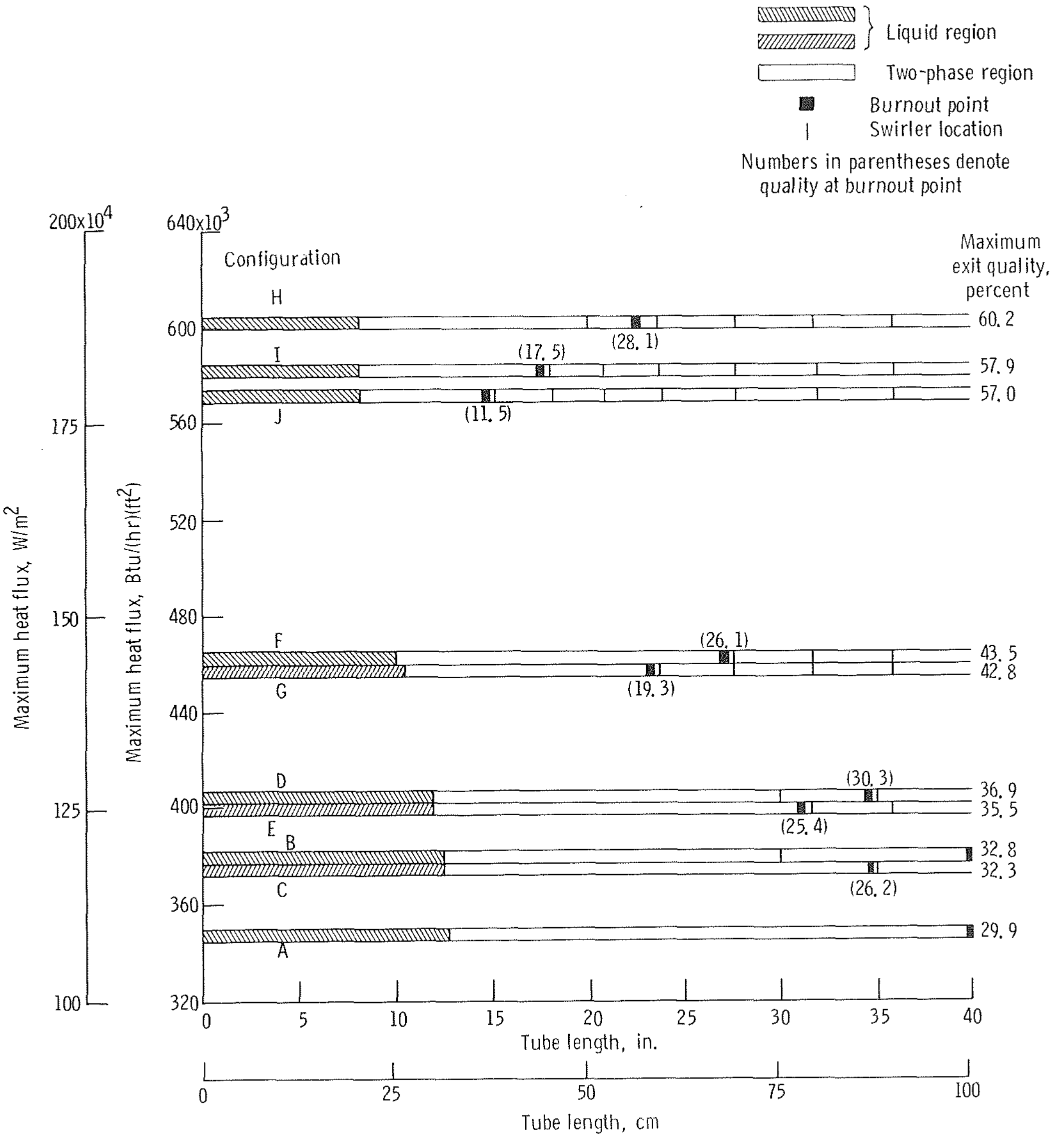

Figure 7. - Summary of results of all configurations tested at flow rate of 400 pounds per hour (5.0×10^{-2} kg/sec).

CONCLUDING REMARKS

The present investigation has indicated that at constant inlet temperature and flow rate the maximum exit quality and the burnout heat flux of boiler tubes can be increased with the proper number and spacing of blade-type helical flow swirlers.

A 100 percent improvement in maximum exit quality (from 0.3 to 0.6) over the plain tube was obtained with a tube containing five swirlers spaced 4 inches (10.2 cm) apart. With this configuration, the pressure drop was increased 58 percent over the plain tube when compared at the same flow rate and exit quality.

Lewis Research Center,
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Cleveland, Ohio, January 30, 1970,
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TABLE I. - EXPERIMENTAL DATA

(a) U. S. customary units

Run	Flow rate, lbm/hr	Heat flux, Btu/(hr)(ft^2)	Inlet temperature, ^oF	Outlet temperature, ^oF	Exit quality, percent	Inlet plenum pressure, psia	Outlet plenum pressure, psia	Temperature profile, ^oF								Remarks
								Inches from inlet								
								5	10	15	20	25	30	35	40	
Configuration A																
1	401	126×10^3	73.5	216.5	----	16.5	16.2	277	---	---	278	273	---	269	275	
2	400	214	76.7	220.0	0.12	18.5	17.3	305	---	---	298	292	295	287	282	
3	403	245	79.5	220.0	.16	19.0	17.0	311	---	---	307	302	296	296	291	
4	398	267	84.0	220.7	.20	20.5	17.5	319	310	---	313	304	306	300	293	
5	402	290	85.5	220.7	.23	22.0	18.0	323	314	---	318	308	---	306	296	
6	397	314	86.0	220.7	.26	23.0	18.0	327	---	---	323	309	309	310	304	
7	400	347	86.0	221.5	.30	25.0	18.0	---	---	---	---	---	---	---	314	Burnout
8	298	218	72.0	217.3	.22	19.0	17.0	301	301	304	298	295	---	---	282	
9	301	275	75.0	218.5	.32	22.0	17.5	315	316	322	311	305	303	---	293	
10	302	310	77.0		.37	----	----	---	---	---	---	---	---	---	---	Burnout
11	302	296	79.5		.35	23.0	17.5	321	321	329	318	310	---	---	298	
12	298	304	83.0		.38	22.7	17.5	323	323	329	319	310	---	---	302	Burnout
13	201	234	77.0	218.0	.45	20.0	17.0	306	303	312	303	294	---	---	286	
14	202	243	77.0	218.0	.46	----	----	---	---	---	---	---	---	---	287	Burnout
Configuration B																
15	397	365×10^3	84.0	225	0.32	26.0	18.0	342	348	353	341	334	---	---	312	
16	404	375	85.0	225	.33	----	----	---	---	---	---	---	---	---	312	Burnout
Configuration C																
17	398	346×10^3	77.0	221	0.29	26.0	18.0	343	346	346	337	330	---	296	293	
18	406	375	80.0	223	.32	27.0	19.0	---	---	---	---	---	---	---	---	Burnout 5 in. from outlet
Configuration D																
19	401	351×10^3	73.5	223	0.30	27	19	424	341	337	337	332	328	321	311	
20	400	375	81	224	.33	28	20	439	350	343	343	337	337	337	315	
21	398	402	84	225	.37	30	20	427	357	350	350	343	340	332	323	Burnout 5 in. from outlet
22	298	306	85	225	.38	26	18	356	328	328	328	322	319	311	303	
23	300	334	85	225	.42	----	----	---	---	---	---	---	---	---	---	Burnout 5 in. from outlet
24	299	328	86	224	.43	----	----	---	---	---	---	---	---	---	---	Burnout
25	203	237	91.5	224	.46	22	17.5	384	310	312	311	306	304	294	294	
26	201	259	91.5	224	.52	----	----	---	---	---	---	---	---	---	301	Burnout 10 in. from outlet
Configuration E																
27	400	351×10^3	81.5	225	0.30	27.5	19	338	341	328	336	330	339	323	312	
28	400	394	85	225	.36	30.0	20	---	354	337	348	341	350	331	321	Burnout 8 in. from outlet

Configuration F																
29	400	349×10^3	69	216.5	0.29	27	19	339	339	336	332	327	321	314	315	
30	403	408	74.5	213	.37	32.5	19.5	341	346	335	334	330	324	315	303	
31	400	442	72.7	213.3	.42	33.8	19.5	348	352	343	343	338	332	321	310	
32	397	455	73	213.3	.44	----	----	---	---	---	---	---	---	---	314	Burnout 12 in. from outlet
Configuration G																
33	401	345×10^3	66	212	0.29	28	18	323	325	325	323	317	312	301	295	
34	405	436	64	213	.39	35	20	355	355	350	347	337	328	323	316	
35	399	459	64	213	.43	----	----	---	---	---	---	---	---	---	321	Burnout 16 in. from outlet
Configuration H																
36	401	351×10^3	80.7	218.5	0.30	29.5	18.5	338	339	337	321	317	315	307	300	
37	401	436	77.5	221	.40	36	19.5	366	365	364	338	340	338	328	320	
38	401	461	80.7	220.7	.44	38	20	374	374	372	342	348	343	336	325	
39	402	500	81.5	223	.43	41	21	385	384	382	354	358	355	346	334	
40	401	530	82.5		.53	44	21	395	393	391	363	366	362	352	338	
41	400	565	83		.57	46	21.5	404	388	396	368	375	371	362	350	
42	406	599	83		.60	----	----	---	---	---	---	---	---	---	---	Burnout 17 in. from outlet
43	300	324	75	220.7	.40	28	18	336	334	330	314	313	319	303	298	
44	301	396	75.5	220.7	.52	34	18.5	359	356	357	327	333	330	323	316	
45	306	479	76	220.7	.65	----	----	---	---	---	345	---	---	---	---	Burnout 25 in. from outlet
46	201	271	72.5	218.5	.53	20.5	17.5	322	316	318	301	301	305	292	277	
47	206	347	75	218.5	.70	----	----	---	---	---	314	---	---	---	---	Burnout 12 in. from outlet
Configuration I																
48	399	349×10^3	82.5	220.7	0.30	29	18.5	334	332	329	315	322	315	309	298	
49	400	436	81.5	221.5	.41	36	20	362	360	355	339	341	337	330	315	
50	402	530	83.5	223	.53	43.5	21	391	382	376	357	365	359	354	336	
51	406	577	83.5	223	.58	----	----	---	---	---	368	---	---	---	350	Burnout 22 in. from outlet
Configuration J																
52	400	347×10^3	72	217	0.29	29	18	346	341	323	319	319	314	304	302	
53	401	503	73.5	221	.49	41	20	390	384	365	359	360	355	346	339	
54	401	568	80.7	221.5	.57	----	----	---	---	---	---	---	---	---	---	Burnout 25 in. from outlet

TABLE I. - Concluded. EXPERIMENTAL DATA

(b) S.I. units

Run	Flow rate, kg/sec	Heat flux, W/m^2	Inlet temperature, K	Outlet temperature, K	Exit quality, percent	Inlet plenum pressure, kN/m^2 abs	Outlet plenum pressure, kN/m^2 abs	Temperature profile, K — Centimeters from inlet: 12.7	25.4	38.1	50.8	63.5	76.2	89.9	101.6	Remarks
							Configuration A									
1	5.045×10^{-2}	397×10^3	296	376	----	113.8	111.7	409	---	---	410	407	---	405	408	
2	5.032	674	298	378	0.12	127.6	119.3	425	---	---	421	418	419	415	412	
3	5.070	772	300		.16	131.0	117.2	428	---	---	426	423	420	420	417	
4	5.007	841	302		.20	141.3	120.7	433	428	---	429	424	426	422	418	
5	5.057	914	303		.23	151.7	124.1	435	430	---	432	427	---	426	420	
6	4.994	989	303		.26	158.6	124.1	437	---	---	435	427	427	428	424	
7	5.032	1093	303	379	.30	172.4	124.1	---	---	---	---	---	---	---	430	Burnout
8	3.749	687	296	376	.22	131.0	117.2	423	423	424	421	419	---	---	412	
9	3.787	866	297	377	.32	151.7	120.7	431	431	434	428	425	424	---	418	
10	3.799	976	298		.37	-----	-----	---	---	---	---	---	---	---	---	Burnout
11	3.799	932	300		.35	158.6	120.7	434	434	438	432	428	---	---	421	
12	3.749	958	302		.38	156.5	120.7	435	435	438	433	428	---	---	423	
13	2.529	737	298		.45	137.9	117.2	426	424	429	424	419	---	---	414	
14	2.541	765	298		.46	-----	-----	---	---	---	---	---	---	---	415	Burnout
							Configuration B									
15	4.994×10^{-2}	1150×10^3	302	381	0.32	179.3	124.1	446	449	452	445	441	---	---	429	
16	5.082	1181	303	381	.33	-----	-----	---	---	---	---	---	---	---	429	Burnout
							Configuration C									
17	5.007×10^{-2}	1090×10^3	298	378	0.29	179.3	124.1	446	448	448	443	439	---	420	418	
18	5.107	1181	300	379	.32	186.2	131.0	---	---	---	---	---	---	---	---	Burnout 12.7 cm from outlet
							Configuration D									
19	5.045×10^{-2}	1106×10^3	296	379	0.30	186.2	131.0	491	445	443	443	440	438	434	428	
20	5.032	1181	301	380	.33	193.1	137.9	499	450	446	446	443	443	443	431	
21	5.007	1266	302	381	.37	206.9	137.9	493	454	450	450	446	444	440	435	Burnout 12.7 cm from outlet
22	3.749	964	303	381	.38	179.3	124.1	453	438	438	438	434	433	428	424	
23	3.774	1052	303	381	.42	-----	-----	---	---	---	---	---	---	---	---	Burnout 12.7 cm from outlet
24	3.761	1033	303	380	.43	-----	-----	---	---	---	---	---	---	---	---	Burnout
25	2.554	747	306	380	.46	151.7	120.7	469	428	429	428	426	424	419	419	
26	2.529	816	306	380	.52	-----	-----	---	---	---	---	---	---	---	423	Burnout 25.4 cm from outlet
							Configuration E									
27	5.032×10^{-2}	1106×10^3	301	381	0.30	189.6	131.0	443	445	438	442	439	444	435	429	
28	5.032	1241	303	381	.36	206.9	137.9	---	452	443	449	445	450	439	434	Burnout 20.6 cm from outlet

Configuration F																
29	5.032×10^{-2}	1099×10	294	376	0.29	186.2	131.0	444	444	442	440	437	434	430	431	
30	5.070	1285	297	374	.37	224.1	134.5	445	448	442	441	439	436	431	424	
31	5.032	1392	296	374	.42	233.1	134.5	449	451	446	446	443	440	434	428	
32	4.994	1433	296	374	.44	-----	-----	---	---	---	---	---	---	---	430	Burnout 30.5 cm from outlet
Configuration G																
33	5.045×10^{-2}	1087×10^{3}	292	373	0.29	193.1	124.1	435	436	436	435	432	429	423	419	
34	4.095	1373	291	374	.39	241.3	137.9	453	453	450	448	443	438	435	431	
35	5.019	1446	291	374	.43	-----	-----	---	---	---	---	---	---	---	434	Burnout 40.7 cm from outlet
Configuration H																
36	5.045×10^{-2}	1106×10^{3}	300	377	0.30	203.4	127.6	443	444	443	434	432	431	426	422	
37	5.045	1373	299	378	.40	248.2	134.5	459	458	458	443	444	443	438	433	
38	5.045	1452	300	378	.44	262.0	137.9	463	463	462	446	449	446	442	436	
39	5.057	1575	301	379	.43	282.7	144.8	469	469	468	452	454	453	448	441	
40	5.045	1670	301		.53	303.4	144.8	475	474	473	457	459	457	451	443	
41	5.032	1780	302		.57	317.1	148.2	480	471	476	460	464	462	457	450	
42	5.107	1887	302		.60	-----	-----	---	---	---	---	---	---	---	---	Burnout 43.2 cm from outlet
43	3.774	1021	297	378	.40	193.1	124.1	442	441	439	430	429	433	424	421	
44	3.787	1247	298	378	.52	234.4	127.6	455	453	454	437	441	439	435	431	
45	3.849	1509	298	378	.65	-----	-----	---	---	---	447	---	---	---	---	Burnout 63.5 cm from outlet
46	2.529	854	296	377	.53	141.3	120.7	434	431	432	423	423	425	418	409	
47	2.591	1093	297	377	.70	-----	-----	---	---	---	430	---	---	---	---	Burnout 30.5 cm from outlet
Configuration I																
48	5.019×10^{-2}	1099×10^{3}	301	378	0.30	200	127.6	441	440	438	431	434	431	427	421	
49	5.032	1373	301	379	.41	248.2	137.9	457	456	453	444	445	443	439	431	
50	5.057	1670	302	379	.53	299.9	144.8	473	468	464	454	458	455	452	442	
51	5.107	1818	302	379	.58	-----	-----	---	---	---	460	---	---	---	450	Burnout 55.9 cm from outlet
Configuration J																
52	5.032×10^{-2}	1093×10^{3}	296	376	0.29	200.0	124.1	448	445	435	433	433	430	424	423	
53	5.045	1584	296	378	.49	282.7	137.9	472	458	458	455	456	453	448	444	
54	5.045	1789	300	378	.57	-----	-----	---	---	---	---	---	---	---	---	Burnout 63.5 cm from outlet

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